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Triadic Digital Integration for Industrial Resilience in Industry 5.0: A Systematic Literature Review

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Abstract: *Global supply chains face unprecedented multidimensional pressures, and the convergence of Blockchain, Internet of Things (IoT), and Artificial Intelligence (AI) marks a paradigmatic shift toward resilient and sustainable industrial ecosystems within the Industry 5.0 framework. To synthesize empirical and conceptual evidence on the triadic integration of Blockchain-IoT-AI concerning supply chain resilience, data security, and industrial sustainability in the Industry 5.0 context. A Systematic Literature Review (SLR) following the PRISMA 2020 protocol, systematically searching the Scopus database (n=2,945 initial records), yielded 25 high-quality final studies (2022-2026). Blockchain-IoT integration significantly enhances supply chain transparency and traceability; AI enables predictive analytics and operational optimization. A Knowledge Graph (30 nodes, 49 edges, density 11.3%) confirms Supply Chain and Blockchain as primary conceptual hubs. Five critical research gaps were identified: Metaverse×Blockchain, Digital Twin×Resilience, Circular Economy×IoT, Smart Grid×Supply Chain, and Computer Vision×Multi-domain.Triadic digital integration offers both a theoretical framework and a practical roadmap for Industry 5.0 adoption, with a selectivity rate of 0.85% (25/2,945), ensuring high-quality evidence synthesis.*

Keywords: *Blockchain; Industry 5.0; Internet of Things; Supply Chain Resilience; Sustainability.*

1. Introduction

The global industrial landscape has undergone a profound transformation driven by the convergence of digital technologies. The World Economic Forum (2023) estimated that digital transformation will generate US$100 trillion in value by 2025. Yet, the fundamental challenge of building resilient, sustainable, and human-centric industrial systems remains unresolved (Ghobakhloo et al., 2025b). The COVID-19 pandemic brutally exposed fundamental vulnerabilities in conventional, centralized, and non-transparent supply chain architectures, triggering a global wave of digital technology adoption (Kamruzzaman et al., 2025). Against this backdrop, Industry 5.0 emerges not as a replacement for Industry 4.0, but as its humanistic evolution: integrating human-centric values, environmental sustainability, and systemic resilience into global production and distribution ecosystems (Ghobakhloo et al., 2025a).

Three empirical phenomena motivate this research. **First,** global supply chain disruption costs reached US$4 trillion annually in the post-pandemic period, with 94% of Fortune 1000 companies reporting supply chain impacts (Verma et al., 2025). **Second,** despite massive technology investments, most organizations implement Blockchain, IoT, or AI in isolation (bilateral at best), resulting in suboptimal outcomes relative to the theoretical potential of integrated systems (Sharifpour et al., 2022). **Third,** academic literature remains fragmented: a preliminary Scopus search yields 2,945 records addressing individual technology integration, but fewer than 1% address triadic synergy (Blockchain-IoT-AI simultaneously), indicating a critical theoretical gap (Mohsen et al., 2026).

The rationalization for triadic integration rests on complementary technological logics: Blockchain provides immutability, transparency, and decentralized trust (Prajapat et al., 2025); IoT delivers real-time connectivity and massive data collection from physical environments (Safeer et al., 2025); AI enables predictive analysis, complex decision automation, and dynamic adaptation to change (Ligar et al., 2024). Each technology addresses only partial dimensions of supply chain vulnerability. When integrated as a triad, they create what this study terms triadic resonance: a multiplicative synergy that exceeds the additive contributions of each technology alone. The motivation of the present study derives from this identified gap. While bilateral integrations (Blockchain-IoT or AI-IoT) have attracted significant scholarly attention (Bawankar et al., 2025; Deepthika & Bhuvaneshwarri, 2025), no systematic, comprehensive review has investigated the simultaneous triadic interplay among all three technologies within the Industry 5.0 paradigm. This constitutes the fundamental justification for the present Systematic Literature Review (SLR). This study addresses four research questions aligned with the Technology-Organization-Environment (TOE) framework and Industry 5.0 imperatives:

a. RQ1: How does the triadic integration of Blockchain-IoT-AI contribute to supply chain resilience within the Industry 5.0 context?

b. RQ2: What factors moderate the effectiveness of triadic digital technology adoption on sustainability and data security outcomes?

c. RQ3: What are the primary technical and managerial challenges impeding the implementation of digital technology integration in global supply chains?

d. RQ4: How has the knowledge map (knowledge graph) of Blockchain-IoT-AI integration evolved in academic literature from 2022 to 2026?

This study aims to: (1) synthesize and map empirical and conceptual evidence on triadic Blockchain-IoT-AI integration in the Industry 5.0 context; (2) identify moderating factors affecting the effectiveness of digital technology adoption on supply chain resilience and sustainability; (3) map debate zones, consensus, and research gaps through knowledge graph analysis; and (4) provide a future research agenda grounded in comprehensive bibliometric analysis. Therefore, the results of this study will be useful for future researchers who want to study the concept of triadic integration of Blockchain-IoT in industry in more depth.

This research contributes on dual levels. Theoretically, it introduces the triadic digital integration construct as a new analytical framework transcending the bilateral approach dominant in the literature. In practice, it provides strategic guidance on adoption for operations managers, policymakers, and industrial systems engineers. The novelty lies in: (1) systematic triadic coverage previously unexplored; (2) integration of SLR-PRISMA analysis with a weighted knowledge graph (30 nodes, 49 edges); and (3) comprehensive mapping from Scopus (n=2,945) through a layered selection process yielding 25 high-quality final studies — with a selectivity rate of 0.85%.

2. Literature Review and Theoretical Framework

2.1. Conceptual Foundations of Triadic Digital Integration

2.1.1. Blockchain: Decentralized Trust Infrastructure

Blockchain is a distributed ledger technology that records transactions immutably, transparently, and in a decentralized manner (Shukri et al., 2024). In the supply chain context, Blockchain offers three fundamental values: (1) product traceability from source to consumer, (2) transaction automation through smart contracts, and (3) elimination of inefficient intermediaries (Prajapat et al., 2025). Knowledge graph analysis confirms Blockchain as the technology hub with the highest degree centrality (0.241) across the 25-study corpus, the sole technology directly connected to four different industry domains. Bawankar et al. (2025) demonstrated a real-world application in pharmaceuticals, in which a Blockchain-IoT traceability system verified drug authenticity and prevented counterfeiting, achieving 99.7% authentication accuracy.

2.1.2. Internet of Things (IoT): Sensor Networks and Real-time Connectivity

IoT refers to an ecosystem of physical devices connected to the internet that can autonomously collect, process, and transmit data in real time (Safeer et al., 2025). In industrial contexts, Industrial IoT (IIoT) creates a real-time visibility layer in production and distribution processes. Frequency analysis of the corpus places IoT as the fourth most frequent theme (n=9), demonstrating its consistent role as a connectivity enabler (Mohanta et al., 2025). Chinte et al. (2025) demonstrated that Blockchain-based decentralized storage architectures for IoT data management significantly enhance both scalability and security compared to centralized alternatives. Salama & Eassa (2024) validated an integrated cloud-based Blockchain model for supply chain management that leverages IoT real-time data to automate procurement decisions.

2.1.3. Artificial Intelligence and Machine Learning

AI and Machine Learning (ML) provide the analytical intelligence layer that transforms raw IoT data into actionable insights (Ainur et al., 2024). In triadic integration, AI serves as the "brain" that processes IoT sensor inputs, analyzes Blockchain transaction patterns, and generates automatic recommendations or decisions. Keyword analysis places AI sixth in frequency (n=7), indicating substantial exploration space relative to Blockchain (n=13) and IoT (n=9). Ligar et al. (2024) developed a coffee supply chain traceability system using Blockchain and ML, in which ML predicted product quality from IoT sensor data, while Blockchain ensured record integrity. Deepthika & Bhuvaneshwarri (2025) mapped AI-Blockchain integration architectures in healthcare data exchange, identifying zero-knowledge proofs as a solution to the transparency-privacy paradox.

2.1.4. Digital Twin: Cyber-Physical Bridge

Digital Twin is a dynamic virtual representation of a physical asset or system, updated in real time through IoT sensor data (Ivanov, 2024). Knowledge graph analysis places Digital Twin as a node with degree=2, a technology underexplored relative to its potential, indicating a significant research gap between Digital Twin and the outcomes of Resilience and Sustainability. Ivanov (2024) conceptualized a 7-element Digital Twin framework in Supply Chain Management, encompassing data, model, simulation, analytics, visualization, decision, and learning dimensions. Raman et al. (2026) explored the evolution of Digital Twins toward the Metaverse as a virtual platform for coordinating flexible and resilient supply chains.

2.2. Underpinning Grand Theories

Four complementary grand theories serve as the epistemological foundation of this study. The Resource-Based View (RBV) regards technology as a strategic asset providing sustainable competitive advantage; in triadic integration, Blockchain-IoT-AI constitutes a bundle of resources that is valuable, rare, inimitable, and non-substitutable (VRIN). Socio-Technical Systems (STS) Theory emphasizes that successful technology implementation depends on a balance between technical and social/organizational dimensions, which is most aligned with Industry 5.0's human-centric paradigm (Ghobakhloo et al., 2025a). Dynamic Capabilities Theory (DCT) (Teece et al., 1997) emphasizes organizational capability to integrate and reconfigure competencies in response to environmental change, directly relevant to supply chain resilience. The Technology-Organization-Environment (TOE) Framework (Tornatzky & Fleischer, 1990) consistently emerges as the dominant explanatory framework in the corpus for variation in adoption effectiveness.

2.3. Knowledge Graph: Intellectual Map of Research

A Knowledge Graph (KG) was constructed from the corpus of 25 selected studies to map semantic relationships among conceptual entities. The KG comprises 30 nodes organized into 5 thematic clusters and 49 edges with three weight levels reflecting the strength of empirical evidence. Citation patterns follow Lotka's Law: 68% of contributing authors appear in only one study, while 12% contribute to three or more studies, reflecting the nascent yet accelerating state of the field (Bradford, 1948).

Table 1. Summary Statistics of Knowledge Graph (30 Nodes, 49 Edges)

Metric	Value	Interpretation
Number of Nodes (N)	30	Conceptual entities from 25 documents
Number of Edges (E)	49	Semantically supported relationships
Graph Density 2E/N(N-1)	0.113 (11.3%)	Sparse — many relationships unexplored
Average Degree	3.27	Each concept is connected to ~3 others
Main Hubs (degree ≥ 5)	5 nodes	Supply Chain, Blockchain, Industry 5.0, Sustainability, Data Security
Isolated Nodes	0	No fully isolated concepts
Strong Edges (w=3)	12 (24.5%)	Backbone — 3+ documents explicitly validated
Moderate Edges (w=2)	25 (51.0%)	Secondary network — consistent in 2 documents
Weak Edges (w=1)	12 (24.5%)	Research frontier — 1 document or implicit

Source: KG construction from 25 selected studies (2022–2026)

Table 2. Main Hubs of the Knowledge Graph — Degree Centrality

Node	Cluster	Degree	Centrality	Role Interpretation
Supply Chain	Outcomes	8	0.276	Super-hub: convergence of all clusters
Blockchain	Digital Technology	7	0.241	Dominant tech hub; 4+ industry domains
Industry 5.0	Theoretical Framework	6	0.207	Paradigm bridge: theory–outcomes
Sustainability	Outcomes	5	0.172	Outcome hub: links technology to ESG
Data Security	Outcomes	5	0.172	Cross-domain hub: health, grid, governance
IoT	Digital Technology	4	0.138	Real-time sensor enabler; core triad
AI / ML	Digital Technology	3	0.103	Predictive analytics layer
Digital Twin	Digital Technology	2	0.069	Cyber-physical bridge; underexplored
Metaverse	Digital Technology	2	0.069	Peripheral node; open frontier

Source: Knowledge Graph centrality analysis — SLR corpus (2022–2026)

Table 3. Identified Research Gaps from Knowledge Graph Analysis

Identified Gap	Missing Link	Recommended Future Study
Metaverse × Technology	Metaverse ↔ Blockchain; Metaverse ↔ IoT	Blockchain & IoT-based Metaverse supply chain architecture
Digital Twin × Outcomes	DT ↔ Resilience; DT ↔ Sustainability	Role of Digital Twin in Supply Chain Disruption Prediction
Circular Economy × Technology	CE ↔ Blockchain; CE ↔ IoT	Blockchain for product lifecycle tracking
Smart Grid × Supply Chain	Energy ↔ SC; Energy ↔ Sustainability	Smart grid integration with green supply chain
Computer Vision × Multi-domain	CV ↔ Pharma; CV ↔ Manufacturing	Computer vision for multi-sector quality control

Source: Peripheral node analysis — Knowledge Graph SLR (2022–2026)

2.4. Bibliometric Analysis of the Corpus

The PRISMA 2020 protocol, complemented by the Biblioshiny/bibliometrix package in R, was used to quantitatively map the field's intellectual structure, including Bradford's Law, Lotka's Law, and keyword co-occurrence analyses. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol is an international standard consisting of a checklist and flowchart. The goals of the PRISMA protocol are transparency: ensuring that the literature selection process is unbiased and well-documented. Replicability: Making it easy for readers or other researchers to trace and repeat the search methods. Completeness: Providing mandatory guidance on what should be included in a research report. The temporal distribution reveals a striking growth pattern: 2022-2023 produced only 1 study passing inclusion criteria, reflecting the initial exploration phase; a significant surge occurred in 2024 (n=6) and reached its peak in 2025 (n=12, representing 48% of the entire corpus), confirming that triadic digital-industrial integration is in an accelerative growth phase.

Table 4. Annual Document Distribution by Category

Year	[F] Foundational	[V] Validation	Total
2022	1	0	1
2023	0	0	0
2024	4	2	6
2025	6	6	12
2026	4 (in progress)	2	6
TOTAL	15	10	25

Source: Biblioshiny Analysis — Annual Scientific Production (2022–2026)

Table 5. Dominant Keyword Frequency — Author Keywords

Keyword / Theme	Frequency	Interpretation
Supply Chain	16	Universal convergence theme; present in nearly all studies
Blockchain	13	Primary foundational technology; widest tech hub
Industry 4.0/5.0	10	Dominant paradigmatic framework; theory-outcome bridge
IoT	9	Real-time connectivity enabler; Blockchain's counterpart
Sustainability	9	Primary outcome: exclusive priority of Industry 5.0
Artificial Intelligence	7	Predictive analytics layer: supports decision-making
Resilience	7	Post-pandemic strategic outcome
Digital Transformation	6	Organizational change process supporting adoption
Smart Contract	4	Blockchain-based transaction automation mechanism
Circular Economy	3	Sustainability outcome: relatively under-explored empirically

Source: Keyword frequency analysis from titles and abstracts of 25 documents (2022–2026)

3. Research Methodology

3.1. Research Design and Alignment with Research Questions

This study employs a Systematic Literature Review (SLR) design following the PRISMA 2020 protocol (Page et al., 2021). The SLR design was specifically chosen for its capacity to address the four research questions: RQ1 and RQ2 are addressed through thematic synthesis and moderating factor analysis of the 25 selected studies; RQ3 is addressed through systematic mapping of implementation challenges across all application domains; and RQ4 is addressed through Knowledge Graph construction and bibliometric trend analysis. A complementary bibliometric approach was applied using Biblioshiny/bibliometrix (v4.3) tools in R to quantitatively map the intellectual structure of the field.

3.2. Search Strategy and Inclusion Criteria

Searches were conducted exclusively on the Scopus database (Elsevier), the largest and most comprehensive database for internationally indexed science, technology, engineering, and social science literature. The search string was designed using Boolean operators AND/OR covering titles, abstracts, and keywords:

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TITLE-ABS-KEY (("blockchain" OR "distributed ledger") AND ("internet of
things" OR "IoT" OR "IIoT") AND ("artificial intelligence" OR "AI" OR
"machine learning") AND ("supply chain" OR "industry 5.0" OR "digital
transformation" OR "industrial resilience" OR "sustainability"))
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Inclusion criteria comprised: peer-reviewed articles or review papers indexed in Scopus; publication period 2022–2026; English language; relevance to integration of at least two of three technologies (Blockchain, IoT, AI) in an industrial or managerial context; and contribution to managerial outcomes (resilience, sustainability, data security, or operational efficiency). These criteria align with the research questions, as managerial relevance directly corresponds to RQ1 (supply chain resilience), RQ2 (sustainability and data security), and RQ3 (implementation challenges). Exclusion criteria included: purely technical studies without managerial implications; non-peer-reviewed articles; duplicate records; and inaccessible full texts.

3.3. PRISMA 2020 Selection Process and Alignment with RQs

Each PRISMA phase serves a specific function in addressing the research questions. Phase 1 (Identification): Systematic search yielded 2,945 initial records using the comprehensive triadic Boolean search string. Phase 2 (Screening): Bibliometric filters applied — Subject Area (Business & Management), document type (Article), language (English), and access (Open Access) — excluded 2,875 records, leaving 70 records for further assessment. Phase 3 (Eligibility): Full-text assessment verified deep relevance to managerial outcomes (directly answering RQ1-RQ3); 45 articles were excluded due to insufficient managerial contribution or domain misalignment. Phase 4 (Included): 25 final studies with a selectivity rate of 25/2,945 = 0.85%, ensuring rigorous quality control.

Table 6. PRISMA 2020 Selection Process — Quantitative Summary

PRISMA Phase	Records	Description
Identification	n = 2,945	Records identified from Scopus using a Boolean search string
Screening (excluded)	n = 2,875	Excluded via bibliometric filters (subject area, doc type, language, OA)
Screening (passed)	n = 70	Records passing all Scopus bibliometric filters
Eligibility (excluded)	n = 45	Excluded after full-text manual review (off-topic, no managerial contribution)
Included (final SLR)	n = 25	Final studies: 10 Foundational [F] + 15 Validation [V] | 19 journals | 68 authors

Source: Adapted from Page et al. (2021) PRISMA 2020 — Research data (Scopus, 2022–2026)

3.4. Data Extraction and Synthesis

Data were extracted using a standardized form covering: bibliographic metadata (author, year, journal, DOI), research design and methods, technologies examined (directly informing RQ4), primary outcomes (RQ1, RQ2), industry/sectoral context (RQ3), grand theories applied, and author-reported limitations. Synthesis employed thematic analysis based on the framework method with four main themes aligned with the research questions: (1) Technology Infrastructure (RQ1, RQ4), (2) Security and Governance (RQ2), (3) Sustainability and Resilience (RQ1, RQ2), and (4) Sectoral Application Domains (RQ3).

3.5. Study Quality Assessment

The quality of each study was assessed using an adapted Mixed Methods Appraisal Tool (MMAT) for technical-managerial studies. Criteria included: clarity of research question, methodological appropriateness, internal and external validity, reporting transparency, and incremental contribution to the field. Only studies achieving adequate appraisal scores were retained in the final analysis. The Foundational-Validation (F-V) classification serves as an additional indicator of epistemic maturity: Foundational studies provide theoretical or framework contributions, while Validation studies provide empirical confirmation.

Table 7. 25 Final Studies — Complete Bibliometric Table (Final Eligibility) Note: [F]=Foundational; [V]=Validation | All documents sourced from Scopus | DOIs available in References.

No	Authors (Year)	Title (Abbreviated)	Journal	Notes
1	Raman et al. (2026)	Enabling Flexible, Resilient, and Sustainable Supply Chains through Metaverse Technologies	Global Journal of Flexible Systems Management	[F]
2	Tankova et al. (2026)	Digital Enablers of the Circular Economy: A Bibliometric and Gender-Inclusive Review	Administrative Sciences	[F]
3	Elhidaoui (2026)	A cost deployment framework for Industry 5.0 in green supply chains (AHP + Fuzzy-QFD)	Cleaner Logistics & SC	[V]
4	Kamruzzaman et al. (2025)	A hybrid framework for prioritizing solutions to mitigate SSC barriers in Industry 5.0	Cleaner Logistics & SC	[V]
5	Mohanta et al. (2025)	Smart-contract-based blockchain-enabled decentralized scheme for smart-grid security	Internet of Things	[V]
6	Mohsen et al. (2026)	Sustainable digitalization of manufacturing supply chains: An integrated framework	Cleaner Logistics & SC	[F]
7	Safeer et al. (2025)	Agri-farming with computer vision, IoT, and blockchain towards climate-smart cultivation	Internet of Things	[V]
8	Subramonian et al. (2026)	Lights-Out Factory: Advancements, Challenges, and Prospects for Fully Autonomous Manufacturing	International Journal of Technology	[F]
9	Ghobakhloo et al. (2025a)	Beyond Industry 4.0: a systematic review of Industry 5.0 technologies and implications	Asia-Pacific Journal of Business Administration	[F]
10	Boufoud & Qafas (2026)	Environmental performance and digitization: Industry 4.0 in ecological transition	Proceedings on Engineering Sciences	[V]
11	Shukri et al. (2024)	A Blockchain-Based Framework for Secure Information Exchange in Digital Governance Systems	Journal of Logistics, Informatics and Service Science	[F]
12	Prajapat et al. (2025)	A Technical Review on Smart Contract Platforms, Languages, and Applications in Blockchain	Proceedings on Engineering Sciences	[F]

No	Authors (Year)	Title (Abbreviated)	Journal	Notes
13	Salama & Eassa (2024)	An Integrated Cloud-based Blockchain Model for Supply Chain Management	Journal of System and Management Sciences	[V]
14	Bawankar et al. (2025)	Blockchain Secured Supply Chain Traceability System for Pharmaceutical Manufacturing Using IoT	Architectural Technology and Sciences	[V]
15	Zaid et al. (2025)	Driving sustainable supply chain performance through digital transformation	Cogent Business & Management	[V]
16	Sharifpour et al. (2022)	Investigating cause-and-effect relationships between supply chain 4.0 technologies	Engineering Management in Production and Services	[V]
17	Ligar et al. (2024)	Design of a Traceability System for a Coffee Supply Chain Based on Blockchain and ML	Journal of Industrial Engineering and Management	[V]
18	Chaudhari et al. (2024)	Strategies for Green SC for Agriculture Equipment Manufacturing: Blockchain-IoT Architecture	International Journal of Mathematical Engineering and Management Sciences	[V]
19	Deepthika & Bhuvaneshwarri (2025)	Healthcare Data Exchange in the Era of Blockchain and AI: A Survey	Architectural Technology and Sciences	[F]
20	Ainur et al. (2024)	Identifying Patterns and Mechanisms of AI Integration in Blockchain for E-voting Network Security	Eastern-European Journal of Enterprise Technologies.	[V]
21	Ghobakhloo et al. (2025b)	Industry 4.0 digital transformation and opportunities for supply chain resilience: strategic roadmap	Production Planning and Control	[F]
22	Verma et al. (2025).	Leveraging Innovative Logistics for Strengthening Supply Chain Resilience	Asian Journal of Interdisciplinary Research	[V]
23	Ivanov (2024)	Conceptualization of a 7-element digital twin framework in SCM	International Journal of Production Research	[F]
24	Chinte et al. (2025)	Blockchain-Based Decentralized Storage for Scalable and Secure IoT Data Management	Journal of Computer, Mechanical, and Management	[V]
25	Bharat & Patil (2025)	Blockchain-Integrated Authentication Framework for Secure Cloud-Based Health Monitoring	Journal of Computer, Mechanical, and Management	[V]

4. Results and Discussion

The results are organized in direct correspondence with the four research questions. Section 4.1 addresses RQ1 (supply chain resilience), Section 4.2 addresses RQ2 (moderating factors and sustainability), Section 4.3 addresses RQ3 (implementation challenges), and Section 4.4 addresses RQ4 (knowledge evolution and mapping).

4.1. RQ1: Triadic Integration and Supply Chain Resilience (Technology Infrastructure)

The 25 final studies span 2022–2026 with 68 unique authors and an average co-authorship of 3.4 authors per document, indicating predominantly collaborative research. International co-authorship at approximately 48% demonstrates that the digital-industrial integration discourse is a global agenda. The F: V category distribution of 40%:60% (10 Foundational, 15 Validation) indicates an active empirical validation phase. The trend of 2025 as the most productive year (n=12, 48%) confirms an acceleration driven by the increasing urgency of post-pandemic supply chain resilience.

Infrastructure findings reveal the dominance of hybrid architecture: combining permissioned Blockchain (Hyperledger Fabric) for enterprise efficiency with IoT edge computing and cloud AI is demonstrably more effective for supply chain applications than pure architectures (Prajapat et al., 2025). Triadic integration contributes to supply chain resilience through three primary mechanisms:

a. Transparency and Traceability: Blockchain's immutability creates end-to-end product traceability. In pharmaceutical applications, Blockchain-IoT traceability systems verified drug authenticity with 99.7% accuracy (Bawankar et al., 2025).

b. Real-time Visibility: IoT sensor networks provide continuous operational monitoring (Safeer et al., 2025). Subramonian et al. (2026) demonstrated that IoT-AI integration is the critical enabler for fully autonomous manufacturing (Lights-Out Factory), while Blockchain guarantees tamper-proof audit trails.

c. Predictive-Adaptive Capability: AI enables proactive disruption management by predicting supply chain risks before they materialize (Ghobakhloo et al., 2025b). Ghobakhloo et al. (2025a) confirmed that Blockchain, IoT, and AI dominate as Industry 5.0 technologies with the highest potential impact on resilience and sustainability.

4.2. RQ2: Moderating Factors on Sustainability and Data Security Outcomes

This section addresses the factors that moderate the effectiveness of triadic adoption, organized into two outcome dimensions: sustainability and data security.

4.2.1. Sustainability Outcomes

Sustainability (n=9 in keywords) and Resilience (n=7) are the most extensively studied outcomes. Triadic integration contributes through three channels: energy efficiency via AI optimization, waste reduction via Blockchain traceability, and precision intervention via real-time IoT monitoring (Mohsen et al., 2026). Kamruzzaman et al. (2025) identified technical barriers (interoperability, scalability) as more significant than organizational barriers in determining the speed of adoption. Zaid et al. (2025) found partial mediation of organizational capabilities between digital transformation and sustainable supply chain performance, confirming that technology alone is insufficient without organizational readiness. Elhidaoui (2026) developed a cost-deployment framework for Industry 5.0 in green supply chains using AHP and Fuzzy-QFD combinations, demonstrating that structured implementation frameworks significantly moderate sustainability outcomes.

4.2.2. Data Security Outcomes

Security and governance issues emerge as critical moderating dimensions. Blockchain significantly enhances data security through cryptography and decentralized consensus (Shukri et al., 2024). However, the Blockchain Trilemma (scalability vs. security vs. decentralization) remains a subject of debate. Deepthika & Bhuvaneshwarri (2025) documented the tension between Blockchain's radical transparency and healthcare data privacy needs, proposing zero-knowledge proofs as a bridging solution. Bharat & Patil (2025) developed a Blockchain authentication framework for wearable health monitoring that integrates biometrics and asymmetric cryptography, thereby demonstrating how security-by-design positively moderates data security outcomes.

4.3. RQ3: Technical and Managerial Challenges in Implementation

Four principal debate zones and implementation challenges were identified from systematic analysis across all 25 studies:

a. Scalability vs. Decentralization (Blockchain Trilemma): The fundamental trade-off between full scalability, high security, and genuine decentralization in mass IoT systems remains unresolved. Layer-2 solutions and sharding show promise but are not yet adequately documented in the managerial literature of this corpus (Prajapat et al., 2025).

b. Radical Transparency vs. Sensitive Data Privacy: Deepthika & Bhuvaneshwarri (2025) document this paradox in healthcare contexts. Zero-knowledge proofs offer a bridging solution, but computational complexity limits mass adoption on constrained infrastructure.

c. Global Adoption Gap: Differences in adoption capacity between developed and developing countries threaten to create a second-generation digital divide. Studies in this corpus provide no concrete solutions to this gap, representing a critical area for future empirical research (Verma et al., 2025).

d. Blockchain Energy Consumption vs. Environmental Sustainability: Boufoud & Qafas (2026) analyze the tension between Proof-of-Work Blockchain energy consumption and Industry 5.0 environmental sustainability goals — migration to Proof-of-Stake is a technical agenda with direct implications for triadic integration viability in green supply chain contexts (Mohsen et al., 2026).

The distribution of sectoral application domains demonstrates broad penetration: Manufacturing (degree=4 in KG) as the primary arena for the 4.0→5.0 transition (Subramonian et al., 2026; Mohsen et al., 2026); Agriculture (degree=3) encompassing smart cultivation (Safeer et al., 2025) and green agricultural supply chains (Chaudhari et al., 2024); Healthcare (degree=3) covering data exchange (Deepthika et al., 2025) and health monitoring (Bharat & Patil, 2025); and Pharmaceuticals (degree=2) for cold chain traceability (Bawankar et al., 2025).

4.4. RQ4: Knowledge Map Evolution of Blockchain-IoT-AI Integration (2022–2026)

The Knowledge Graph analysis maps the intellectual evolution of the field. Betweenness centrality analysis identifies three primary hubs bridging clusters: (1) Blockchain, connecting the technology cluster to all industry domains; (2) Industry 5.0, a bridge between theoretical frameworks and management outcomes, the sole evolutionary edge (Industry 4.0→5.0, w=3); and (3) Supply Chain, convergence point of nearly all pathways. Three dominant conceptual pathways are identified from the knowledge graph: Pathway 1 (paradigm evolution): Industry 4.0 → Industry 5.0 → Supply Chain → Resilience; Pathway 2 (technology implementation): Blockchain → IoT → Supply Chain → Traceability → Pharma/Agriculture; Pathway 3 (cross-sector security): Blockchain → Smart Contract → Data Security → Health/Governance/Smart Grid. The 11.3% KG density confirms that 89% of potential inter-concept relationships remain empirically unexplored, indicating the field is still in active formation.

4.5. Theoretical and Practical Implications

Theoretically, this research confirms the relevance of RBV, STS, DCT, and TOE frameworks, while proposing the new construct of triadic resonance — the capability of three technologies to mutually reinforce and multiplicatively amplify impacts: Triadic Resonance = f(Blockchain × IoT × AI) > f(Blockchain) + f(IoT) + f(AI). The TOE Framework emerges as the dominant explanatory framework for variation in adoption effectiveness, consistent across manufacturing, agriculture, and healthcare domains. In practice, modular adoption recommendations are proposed: begin with IoT for real-time visibility (lowest organizational change requirement), add Blockchain for immutability and smart contracts (moderate complexity), and then integrate AI for predictive analytics (highest complexity). This phased approach is more realistic and reduces the risk of implementation failure. For policymakers, Public-Private Partnership (PPP) models for financing shared digital infrastructure in SMEs in developing countries emerge as a consistent recommendation across the corpus (Verma et al., 2025; Zaid et al., 2025).

5. Conclusion

5.1 Summary of Findings Aligned with Research Questions

In response to RQ1, this study confirms that the triadic integration of Blockchain-IoT-AI demonstrably contributes to supply chain resilience through three mechanisms: transparency/traceability (Blockchain), real-time visibility (IoT), and predictive and adaptive capabilities (AI). Responding to RQ2, organizational readiness, interoperability, and institutional context emerge as the primary moderating factors in the effectiveness of triadic adoption on sustainability and data security outcomes (Zaid et al., 2025; Kamruzzaman et al., 2025). Responding to RQ3, the Blockchain Trilemma, energy consumption, and the global adoption gap constitute the most significant implementation barriers, with no consensus solutions yet documented in the managerial literature. Responding to RQ4, a Knowledge Graph with 30 nodes and 49 edges empirically confirms the field's intellectual structure, with five primary conceptual hubs (Supply Chain, Blockchain, Industry 5.0, Sustainability, Data Security) and an 11.3% density, confirming 89% of potential relationships remain unexplored.

5.2. Research Contributions

Theoretical contributions include: (1) the triadic digital integration and triadic resonance constructs as new analytical frameworks; (2) confirmation of TOE as the dominant explanatory framework in multi-technology Industry 5.0 contexts; and (3) the first weighted Knowledge Graph mapping 30 nodes and 49 edges from the 2022–2026 triadic corpus. Methodological contributions include: (1) demonstration of the PRISMA 2020 + Biblioshiny/bibliometrix combination for rapidly evolving field analysis; (2) a reproducible selection protocol from 2,945 to 70 (screening) to 25 (eligibility) studies with full transparency; and (3) Foundational-Validation classification as an epistemic maturity indicator. Practical contributions include: (1) modular triadic adoption guidelines for practitioners; (2) differentiated policy recommendations for developing countries; and (3) a research gap map with specific missing links.

5.3. Limitations and Future Research

This study acknowledges three primary limitations with empirically grounded implications. First, database coverage is limited to Scopus; adding Web of Science and Google Scholar could reveal additional nodes and relationships in the knowledge graph, as these databases index different journal populations (Page et al., 2021). Methodological studies consistently demonstrate that multi-database searches increase recall by 20-40% in systematic reviews (Kamruzzaman et al., 2025). Second, KG edge weighting is qualitative based on frequency and context; for corpora exceeding 100 documents, VOSviewer or R-bibliometrix is recommended for automated co-occurrence matrix-based weighting (Tankova et al., 2026). Third, the 2022–2026 temporal boundary may exclude important theoretical foundations from prior periods, particularly seminal Blockchain-IoT integration works from 2018-2021 that form the conceptual basis of several included studies (Sharifpour et al., 2022).

Based on knowledge graph gap analysis, thematic findings, and the identified limitations, the following empirically-grounded future research agenda is recommended:

a. Metaverse×Blockchain and Digital Twin×Resilience empirical studies: These represent the two most critical missing links in the current knowledge graph. Ivanov (2024) provides a theoretical foundation for Digital Twin-resilience integration that awaits empirical validation; Raman et al. (2026) similarly call for empirical testing of Metaverse-based supply chain architectures.

b. Longitudinal research on triadic adoption impact: Measuring the temporal impact trajectory of triadic adoption to understand the technology benefit curve and investment inflection points. Zaid et al. (2025) confirm that cross-sectional studies are insufficient for capturing organizational learning effects.

c. Cross-country comparative studies: Investigating institutional context differences in Industry 5.0 adoption between developing and developed countries, particularly focusing on the adoption gap documented by Verma et al. (2025). The TOE framework provides a validated theoretical lens for such comparative work.

d. Standardized measurement scales for triadic digital integration: Development of psychometrically validated scales to enable more systematic empirical evidence accumulation, as called for by Ghobakhloo et al. (2025b) in their strategic roadmap.

e. Blockchain Trilemma solutions in supply chain contexts: Investigation of Layer-2, sharding, and zero-knowledge proof approaches with a managerial lens (Prajapat et al., 2025; Deepthika & Bhuvaneshwarri, 2025), particularly for developing-country SME contexts where computational constraints are more severe.

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